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Title: Effect of Electron Beam Oscillation Figures on Weld Surface Condition and Cross Sectional Morphology

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Effect of Electron Beam Oscillation Figures on Weld Surface Condition and Cross Sectional Morphology

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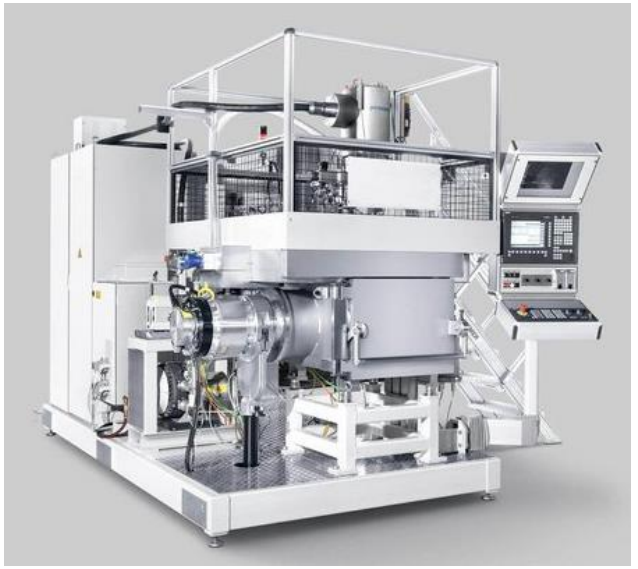
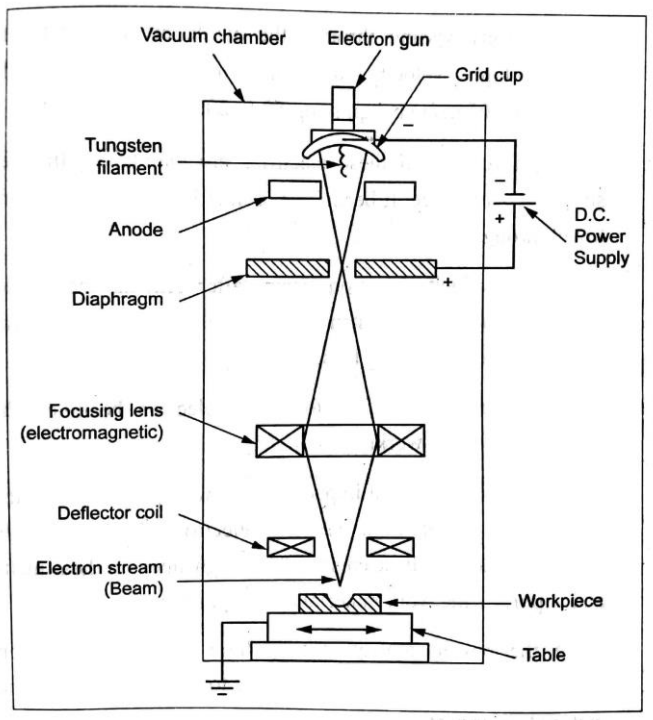
Overview

1. Problem
    1. Preliminary experiments showed weld depth and surface condition are not consistent among different oscillation figures
2. Investigation
    1. Study the circle and concentric circle figures, and directional variants of these
    2. Measure the effect of frequency on the figure
    3. Produce beam figures of equal diameter
    4. Produce welds using equal diameter beam figures
    5. Correlate weld depth, surface condition, and root defects with the beam figure

Electron Beam Welding

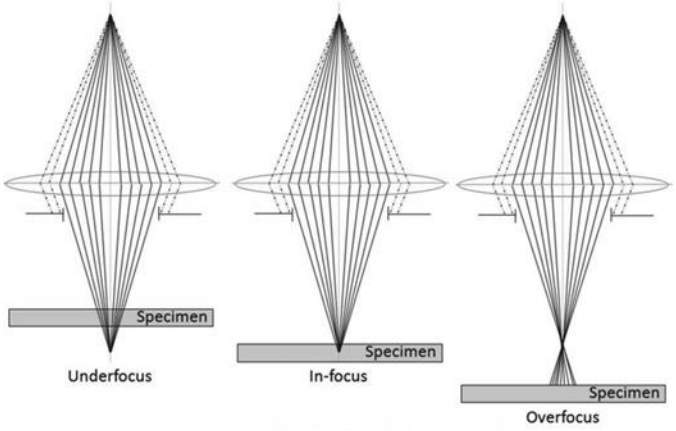
- Welding performed within a high vacuum chamber.
- High voltage (60 kV) drives a narrow beam of electrons at high velocity to imping on the workpiece surface.
- Kinetic energy of the beam produces melting for fusion welding of the workpiece.
- Magnetic fields focus the beam controlling it's size & shape.
- The weld shape and depth is controlled by adjusting beam power, and beam size & shape at the workpiece.
- Power density, (A x V)/Area, is controlled by beam focus or beam deflection.



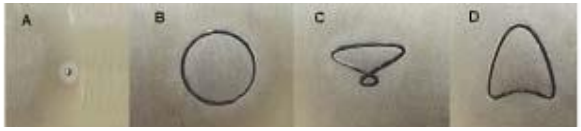


Focus Current and Beam Oscillation

- There are two ways to achieve an optimal beam size and energy distribution
  - Defocus Beam
    - Under focus: Focal point is below the surface.
    - Sharp focus: Focal point is at the surface.
    - Over focus: Focal point is above surface.

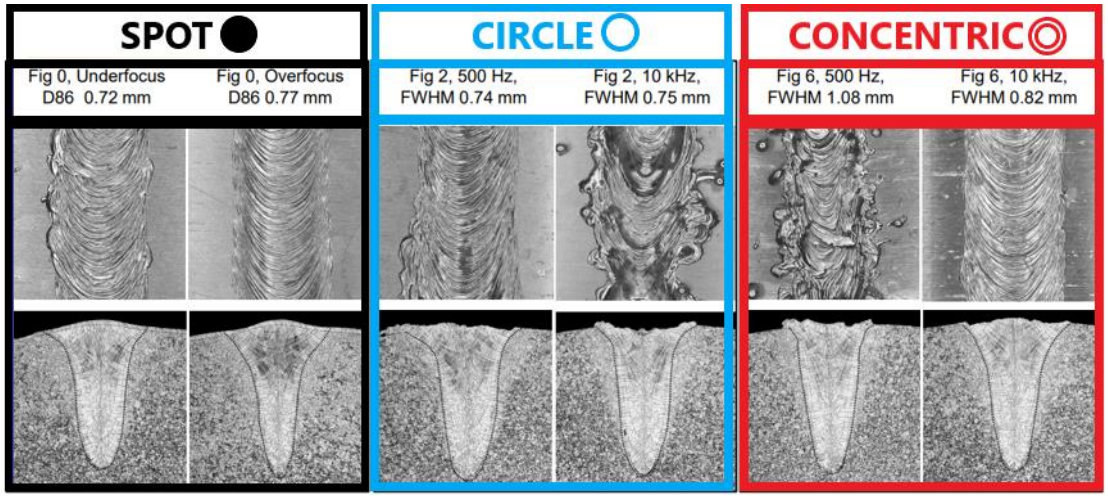


  - Beam Oscillation
    - The sharp focus beam is oscillated in a pattern such as a circle, figure eight, etc.

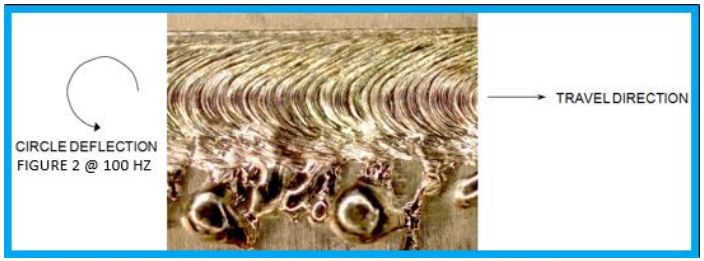


Beam Oscillation affects Weld Surface Roughness

- Preliminary experiments with beam oscillation yielded smooth and rough welds.
  - Roughness varied with figure type and frequency.
  - Welds made on Ta-10W



  - Roughness varied with figure generation direction and weld travel direction.



Investigation of Beam Oscillation Figures

- Figures included a single circle, 10 concentric circles, and variants in the figure formation sequence
- The digital figures are composed of 1000 discrete beam spots
- Path of figure formation relative to welding direction

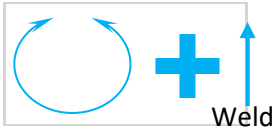
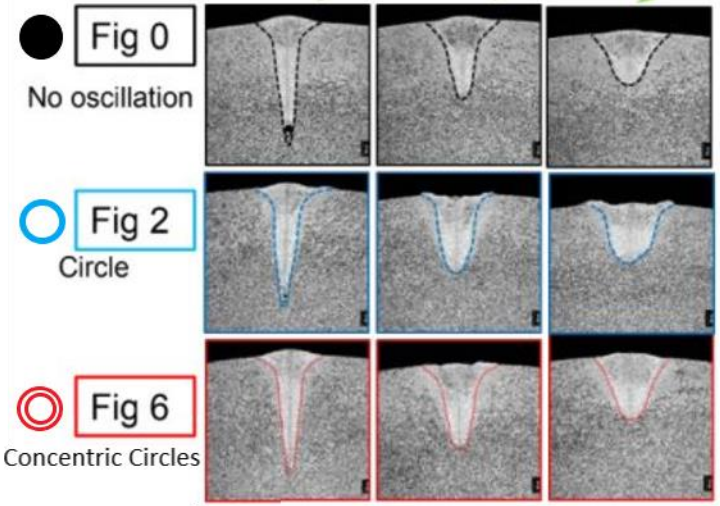


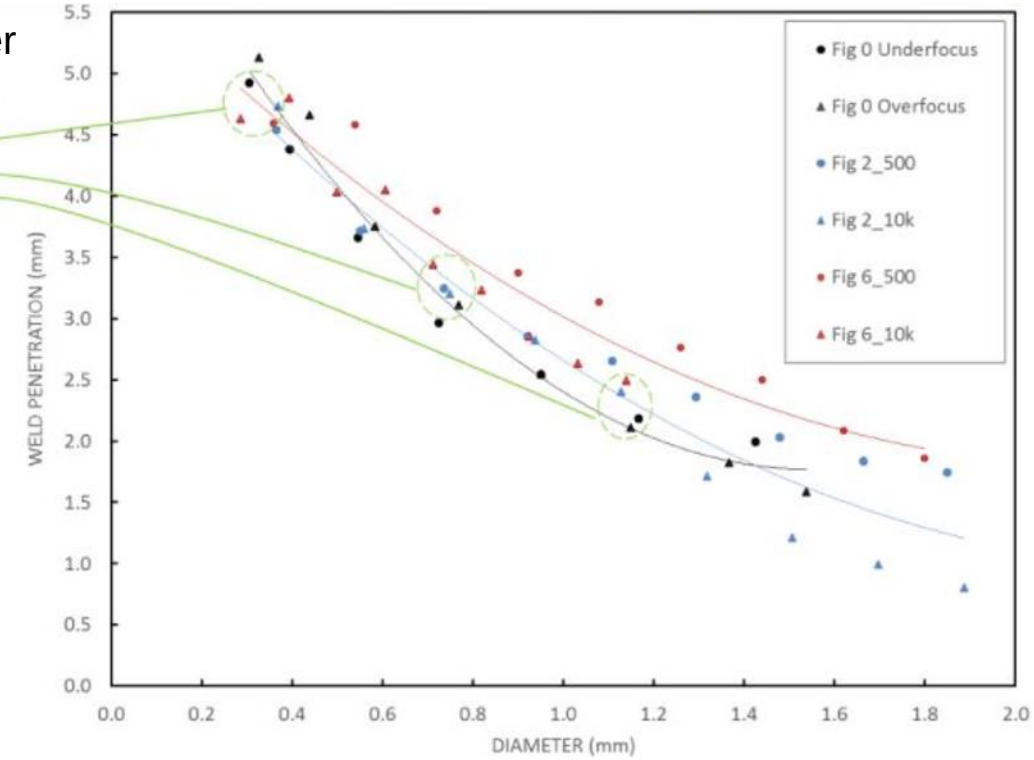
Figure Description							
Fig 2	Counter clockwise circle				Weld Direction		
Fig 16	Split circle, alternating halves, top to bottom						
Fig 18	Random order circle						
Fig 6	Counter clockwise concentric circles, outside to inside						
Fig 15	Split concentric circles, alternating halves, top to bottom, outside to inside						
Fig 17	Random order concentric circles						

Producing Equal Weld Depths with Beam Figures

For comparison of beam figures, welds of equal depth are desirable.

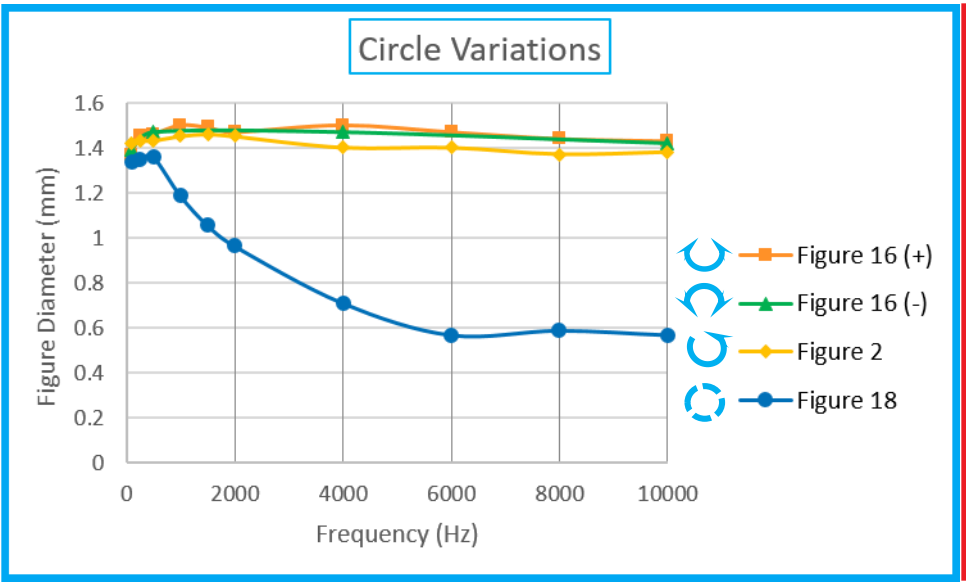
- Equivalent beam and figure diameter yields similar size and shape welds.

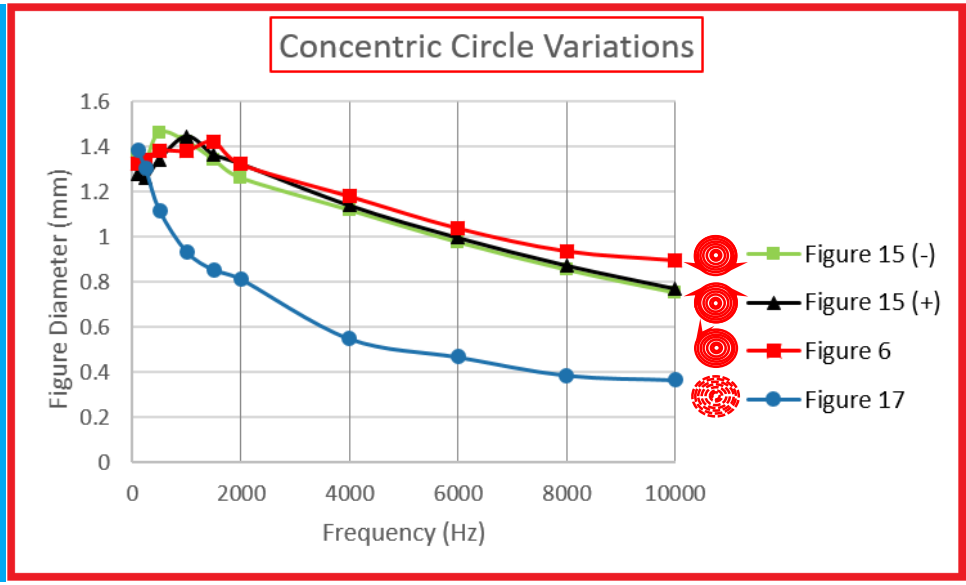




Frequency Effect on Beam Figure Diameter

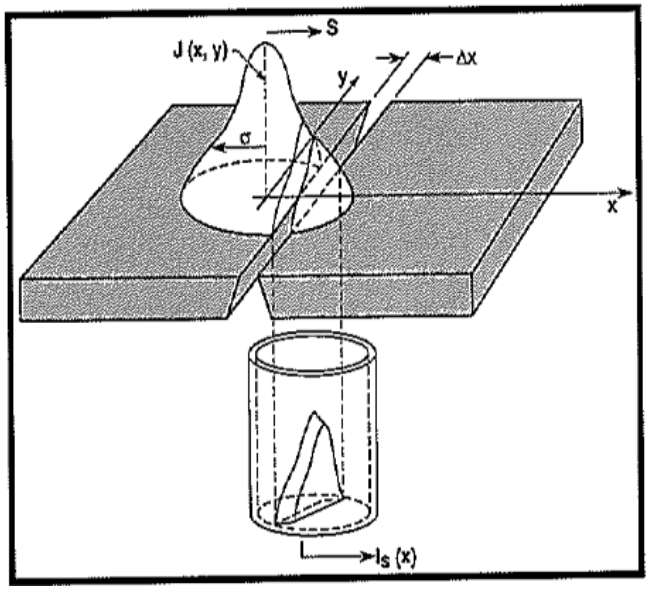
- As frequency increases, figure diameter decreases and weld depth increases.
- To compare different figures, welds of equal depth are desirable.
- A consistent figure diameter should yield consistent weld depth for the various figures
- Frequency was held constant at 500 and 10 kHz.

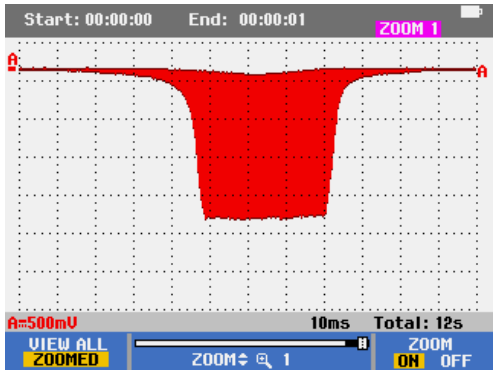




Measuring the Beam Figure Diameter

- The beam figure is passed across the slit in the faraday cup at constant velocity
- As the beam traverses the faraday cup, the voltage output of the beam is recorded on an oscilloscope.
- The beam figure diameter is calculated.
  - For this work, the peak to peak width was used

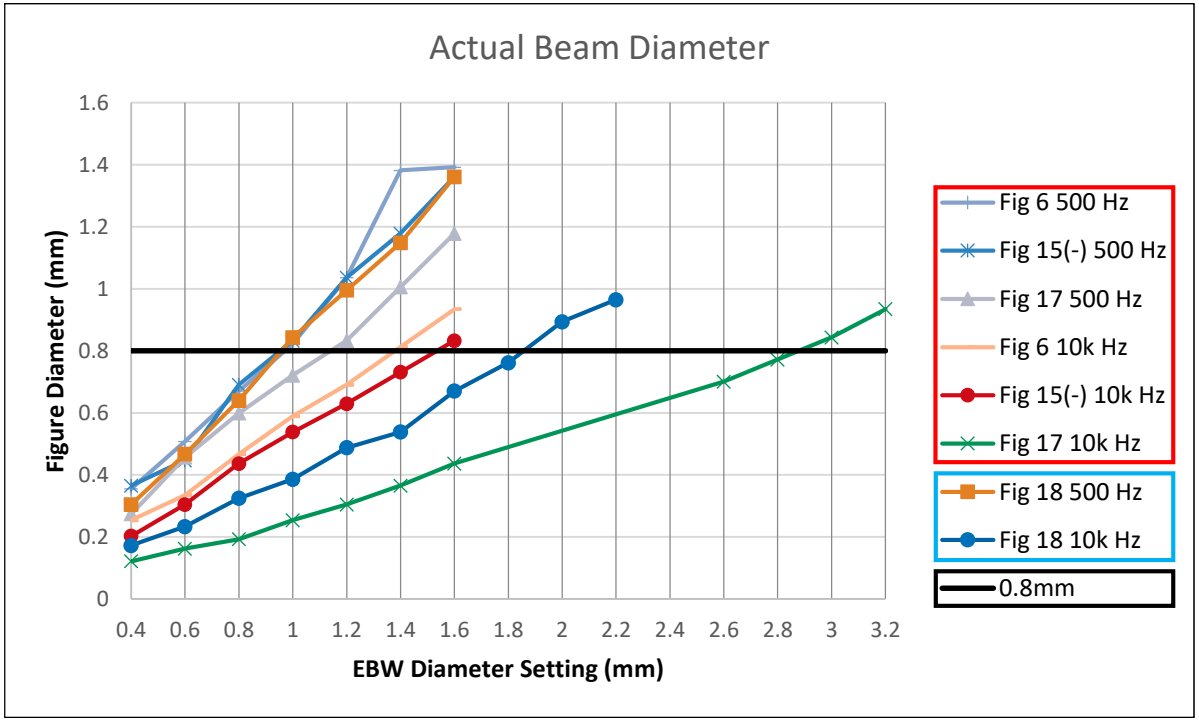




Producing an Equal Beam Figure Diameter

EBW Diameter Setting vs. Actual Diameter

- The figure diameter was measured at both 500 and 10k Hz for each figure
- The figure diameter setting was determined to yield an actual diameter of 0.8 mm for welding.

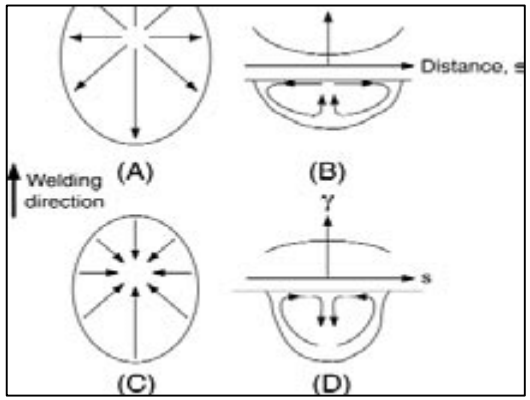


This table does not include Figure 16 and Figure 2. These figures were proven to not change in diameter

Comparison of Ta-10W and Stainless Steel EBW

Ta-10W

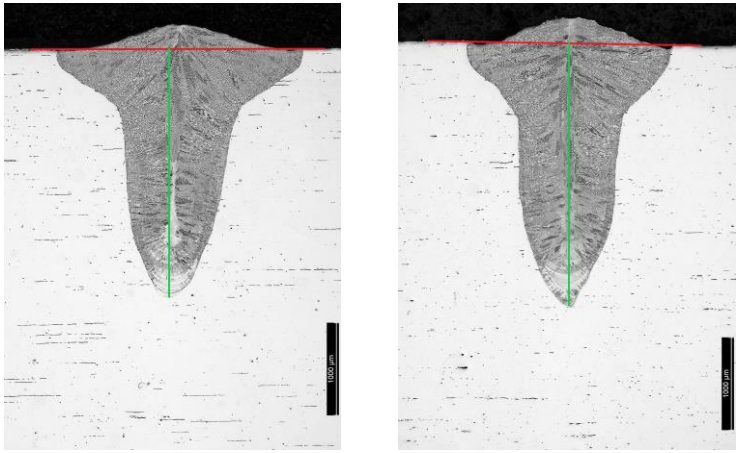
- Very high melting temp (3025°C)
- Requires high power to melt and vaporize, 60mA beam current
- High thermal conductivity, weld cools and solidifies very quickly



Marangoni Flow

Stainless Steel

- Melting temperature ½ Ta-10W (1425˚C)
- Requires < 30mA beam current
- Low thermal conductivity, so weld cools and solidifies slowly
- Sulfur level influences surface width due to Marangoni flow

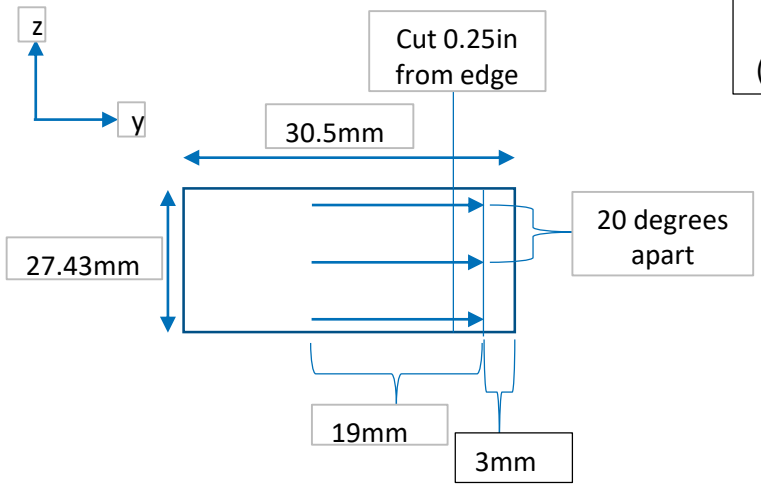


CCW circle at 10k Hz, low sulfur (left) and high sulfur (right)

Welding Parameters

Ta-10W

- 60mA beam current
- Focus current 1933mA
- 19mm weld length
- Weld speed 25.4mm/s
- 18 welds made on 27.43 mm diameter round bar, 20 degrees apart
  - Made two extra defocus welds as experiments
- Calibration value set to 8200
- Welds made 3 at a time, 120 degrees apart, and cooled between sets



Stainless Steel

- 30mA beam current
- Focus current 1936mA
- Weld speed 25.4mm/s
- 26mm weld length
- 16 welds made on flat bars 3.3mm apart
- Calibration value set to 8200
- Welds made 3 at a time, cooled between sets

Point Side (Front)

Weld # 1 Fig 2 500 Hz	Weld # 5 Fig 6 500 Hz	Weld # 2 Fig 16(+) 500 Hz	Weld # 6 Fig 15(+) 500 Hz
Weld # 8 Fig 17 500 Hz	Weld # 4 Fig 18 500 Hz	Weld # 7 Fig 15(-) 500 Hz	Weld # 3 Fig 16(-) 500 Hz

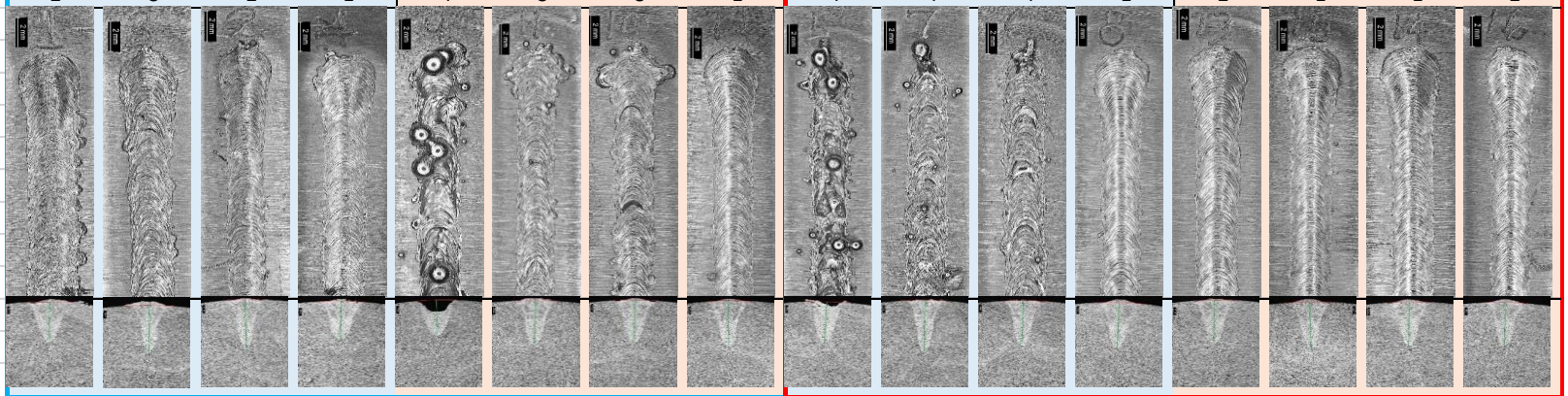
X Side (Back)

Weld # 9 Fig 2 10k Hz	Weld # 13 Fig 6 10k Hz	Weld # 10 Fig 16(+) 10k Hz	Weld # 14 Fig 15(+) 10k Hz
Weld # 16 Fig 17 10k Hz	Weld # 12 Fig 18 10k Hz	Weld # 15 Fig 15(-) 10k Hz	Weld # 11 Fig 16(-) 10k Hz

Welding Results, Surface Rating

Ta-10W

	Circle Variants: 2- CCW, 16- Split, 18- Random								Concentric Variants: 6- CCW, 15- Split, 17- Random							
Figure #	2	16(-)	16(+)	18	2	16(-)	16(+)	18	6	15(-)	15(+)	17	6	15(-)	15(+)	17
Frequency (Hz)	500				10k				500				10k			
Weld Depth (mm)	2.6	3.2	3.1	2.4	2.3	2.8	2.8	2.9	2.7	3.3	2.9	2.9	2.8	3.0	2.8	2.9
FWHM Width (mm)	1.2	0.8	0.9	1.2	1.3	1.0	1.1	1.0	1.1	0.8	1.0	1.1	1.1	1.0	1.0	1.0
Surface Width (mm)	2.4	2.5	2.1	2.3	2.1	2.3	2.2	2.3	2.2	2.2	2.2	2.3	2.3	2.4	2.3	2.2
Surface Rating (1-5)	2	3	2	1	4	3	3	1	4	4	4	1	2	1	1	2

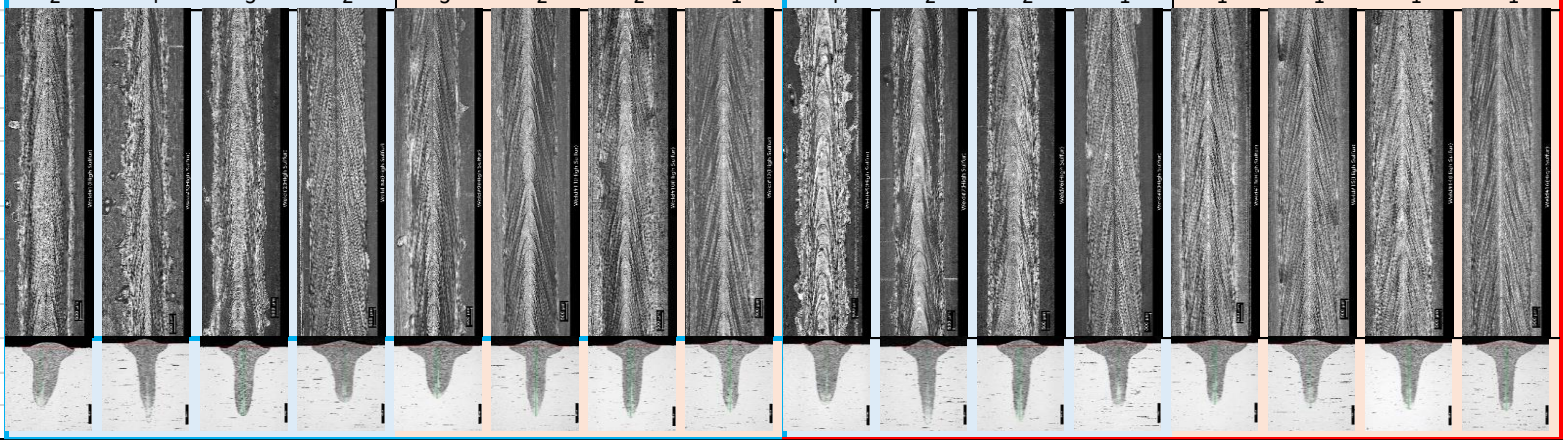


- Random figures very good at both frequencies
- Concentric variants very good at high frequency, independent of figure variant
- Circle variants good at low frequency, independent of figure variants
- Directional figures have greater weld depth than other figures
- Random figures have consistent surface width across both concentric and circles

Welding Results, Surface Rating

High Sulfur Stainless Steel

	Circle Variants: 2- CCW, 16- Split, 18- Random								Concentric Variants: 6- CCW, 15- Split, 17- Random							
Figure	2	16(-)	16(+)	18	2	16(-)	16(+)	18	6	15(-)	15(+)	17	6	15(-)	15(+)	17
Frequency	500				10000				500				10000			
Weld Depth (mm)	3.0	4.2	3.6	2.9	2.8	3.8	3.7	3.4	3.3	4.0	3.9	3.2	3.1	3.3	3.4	3.3
FWHM Width (mm)	1.0	0.7	0.7	0.9	1.0	0.7	0.7	0.7	0.9	0.6	0.6	0.7	0.7	0.7	0.7	0.7
Surface Width (mm)	2.1	1.8	1.9	2.3	2.2	2.2	2.2	2.3	2.2	1.8	2.0	2.3	2.3	2.4	2.5	2.4
Surface Rating	2	4	3	2	3	2	2	1	4	2	2	1	1	1	1	1

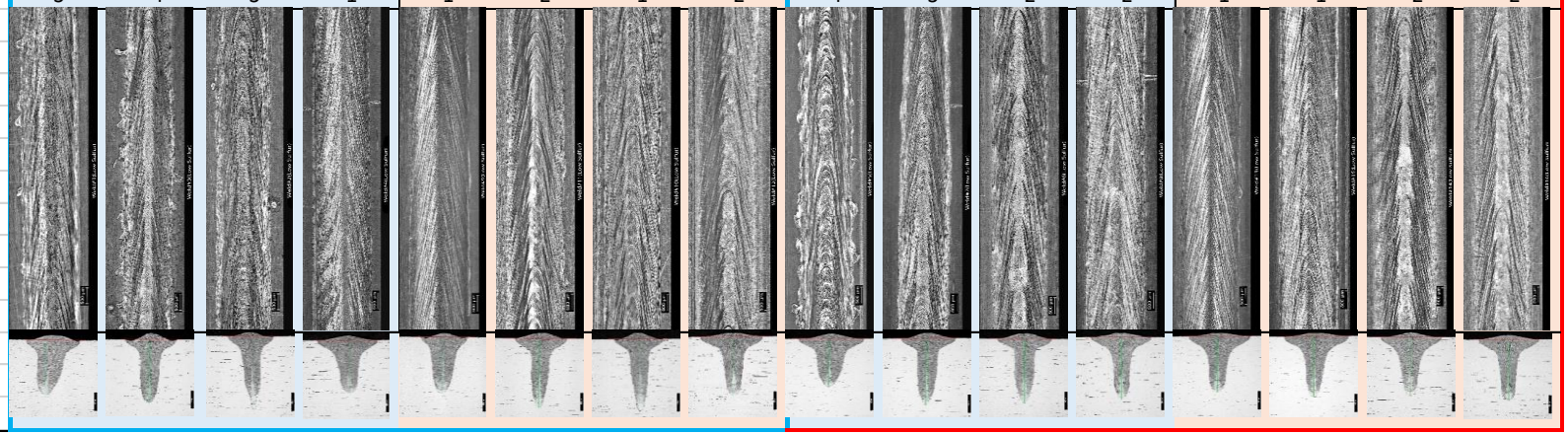


- Random figures very good at both frequencies
- All variants best at high frequency
- Direction does not affect surface quality
- Directional figures have highest weld depth; deeper welds are narrower
- Surface width also scales with weld depth

Welding Results, Surface Rating

Low Sulfur Stainless Steel

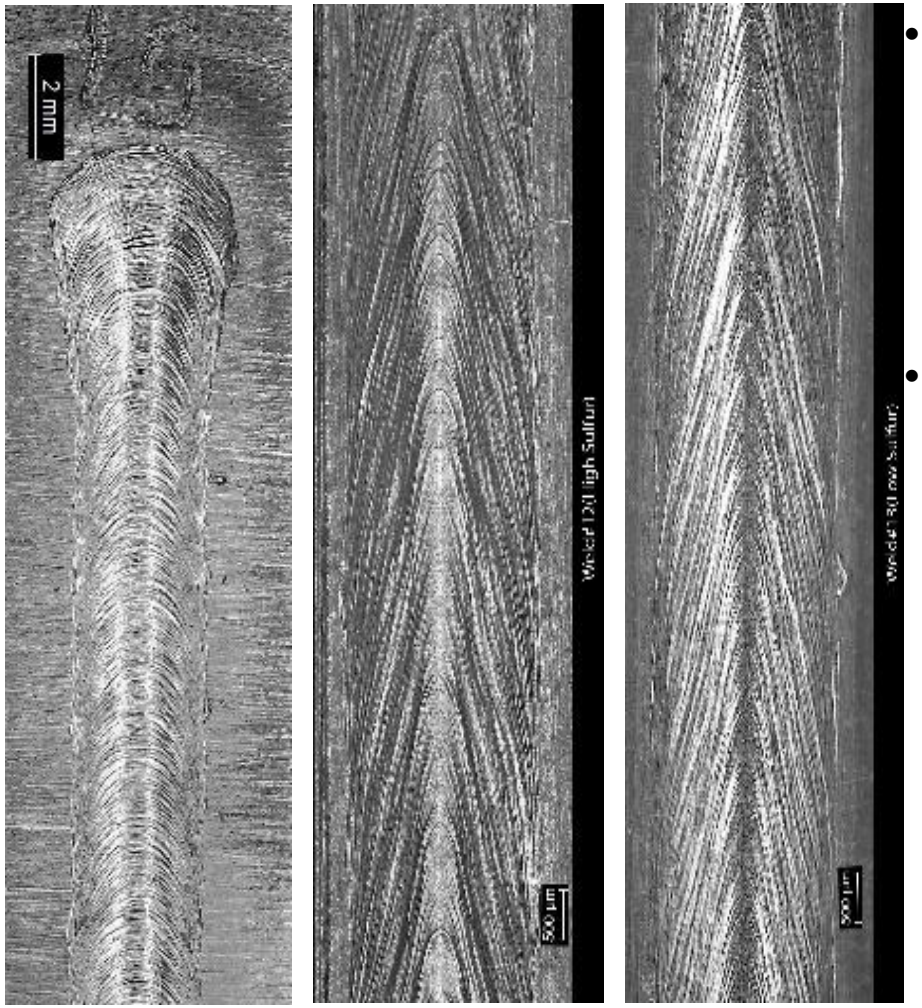
	Circle Variants: 2- CCW, 16- Split, 18- Random								Concentric Variants: 6- CCW, 15- Split, 17- Random							
Figure	2	16(-)	16(+)	18	2	16(-)	16(+)	18	6	15(-)	15(+)	17	6	15(-)	15(+)	17
Frequency	500				10000				500				10000			
Weld Depth (mm)	3.1	4.0	3.5	2.9	2.7	3.6	3.7	3.5	3.1	3.9	3.8	3.3	3.1	3.2	3.4	3.4
FWHM Width (mm)	1.0	0.7	0.8	0.8	1.1	0.8	0.8	0.7	0.9	0.7	0.7	0.8	0.7	0.8	0.7	0.7
Surface Width (mm)	2.2	1.9	2.1	2.5	2.7	2.2	2.2	2.5	2.3	2.0	2.1	2.6	2.5	2.5	2.6	2.5
Surface Rating	3	4	3	1	1	2	1	2	4	3	2	2	1	1	2	2



- Random figures very good at both frequencies
- All variants best at high frequency
- Negative direction is better for all but high frequency concentric variants
- Surface width decreases as weld depth increases

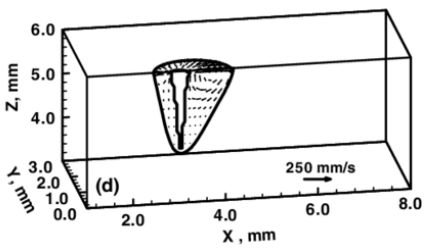
Weld Surface Comparison

Ta-10W **High Sulfur** **Low Sulfur**

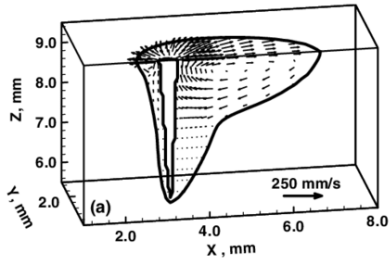


- Ta-10W:
  - High melting temperature and thermal conductivity restricts the weld pool/keyhole size and results in a rounded solidification ripple pattern
- Stainless Steel:
  - Low melting temperature and thermal conductivity results in an elongated weld pool/keyhole and V-shaped solidification ripple pattern

Tantalum

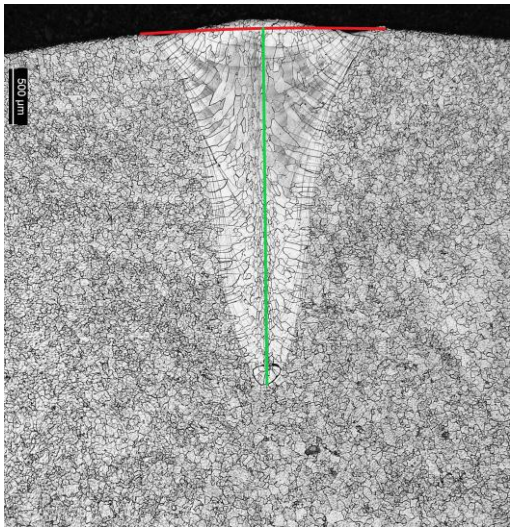


Stainless Steel



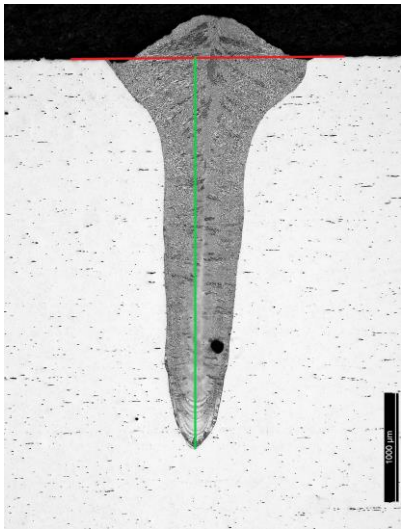
Weld Cross Section Morphology

Ta-10W

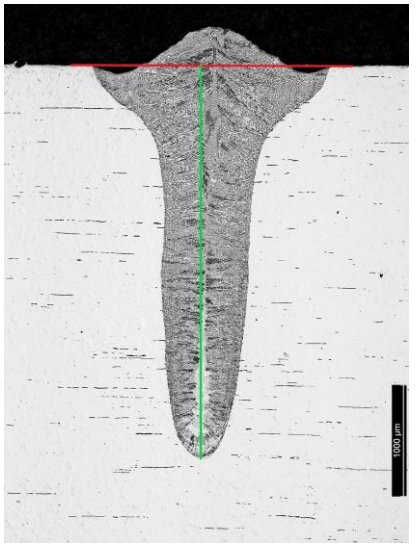


- Ta-10W:
  - Triangular shape, less nail head
  - High melting temperature, only the high energy density core of the beam figure results in melting
  - Wider than stainless steel at ½ depth
  - Lower surface profile than stainless steel

High Sulfur



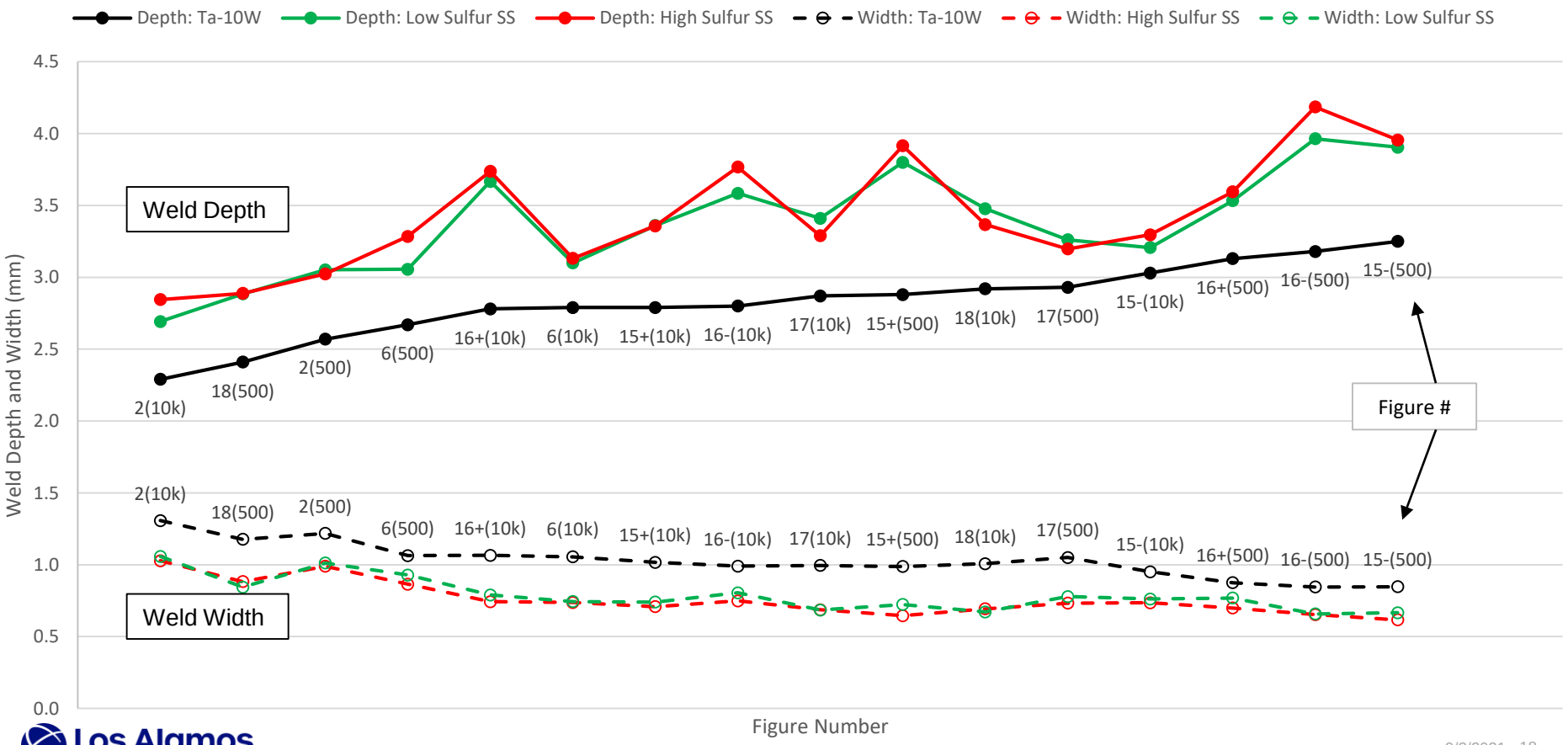
Low Sulfur



- Stainless Steel:
  - More pronounced nail head feature
  - Low melting temperature, low energy density perimeter of the beam figure results in melting and forming nail head
  - Low sulfur wider at surface due to Marangoni flow

Weld Depth and Width Consistency

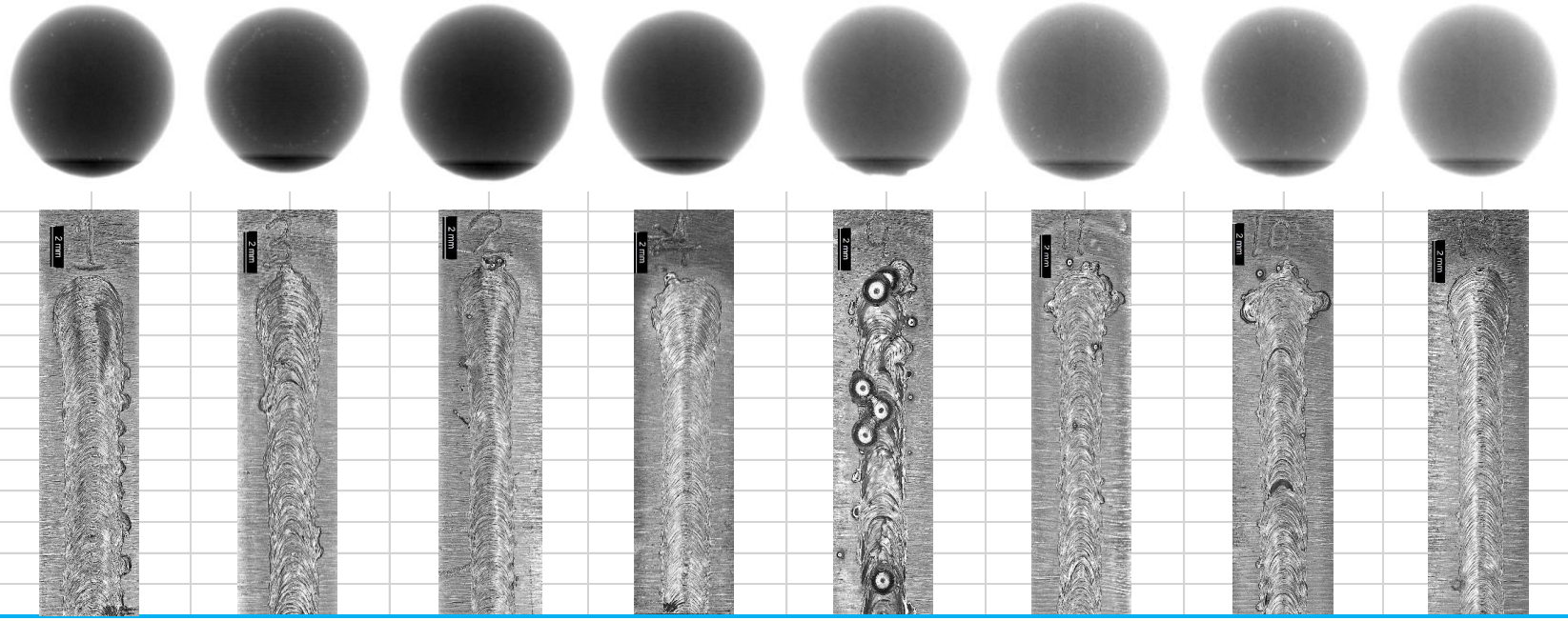
- Weld depth and width at ½ depth follow a consistent trend dependent on the beam figure and independent of material type at low frequency
- Directional figures deep and wider, CCW figures shallower and narrower



Root Defects, Circle Figures

- Circumferential welds were made to take radiography samples
- Root defects appear in both Ta-10W and stainless steel welds
- All directional figures have root defects
- Primarily the low surface quality welds have root defects

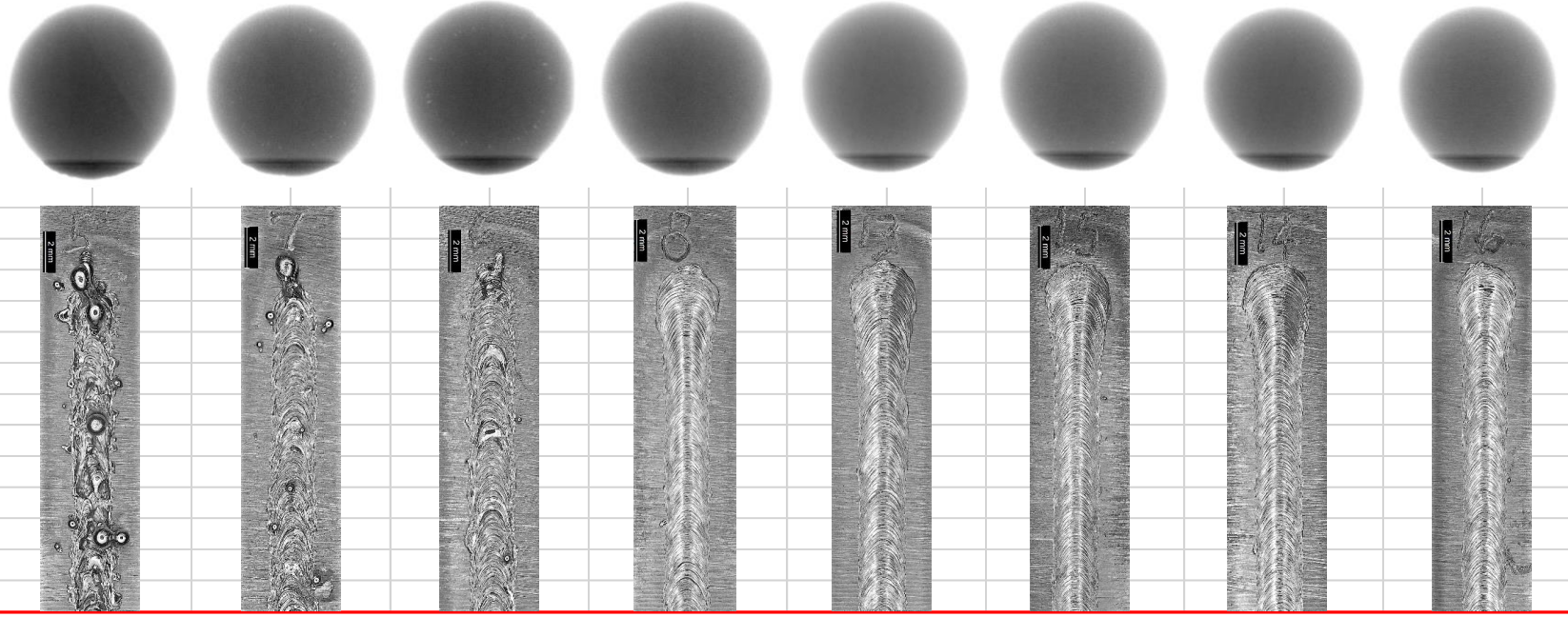
Figure #	2	16(-)	16(+)	18	2	16(-)	16(+)	18
Frequency (Hz)	500	500	500	500	10k	10k	10k	10k
Surface Quality	2	3	2	1	4	3	3	1



Root Defects, Concentric Figures

- Root defects appear in both Ta-10W and stainless steel welds
- Only directional figures have root defects
- Defects less severe in concentric compared to circles

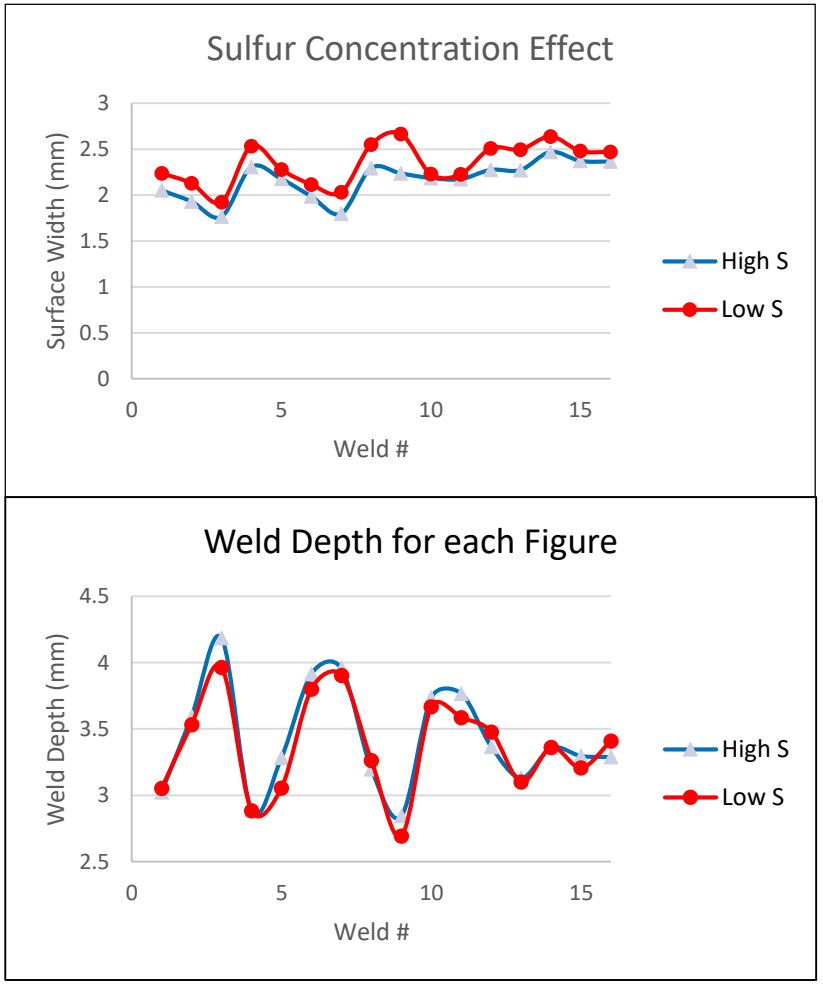
Figure #	6	15(-)	15(+)	17	6	15(-)	15(+)	17
Frequency (Hz)	500	500	500	500	10k	10k	10k	10k
Surface Quality	4	4	4	1	2	1	1	2



Sulfur Concentration

Marangoni Fluid Flow

- Low sulfur welds are shallower and wider at surface
- Higher sulfur are narrower and deeper
- Marangoni flow is consistent for every weld, but has a small effect in electron beam keyhole welds



Conclusions

- Surface Condition
  - Ta-10W welds strongly affected by figures due to high melting temperature, thermal conductivity, and rapid solidification
  - Stainless steel less affected because of higher fluid flow and slower solidification
  - Random figures at both frequencies have very good surface quality on both materials
  - Marangoni effect causes low sulfur stainless to have wider surface than high sulfur
  - Stainless steel welds have pronounced nail head feature
- Root Defects
  - High surface quality welds have no root defects, only concentric directional (-) at high frequency has minimal defects
  - Almost all directional figures on Ta-10W and both stainless have root defects, figure formation may cause keyhole instability
  - Root defects associated with an unstable keyhole and spiking
- Weld Depth
  - The trends in weld shape for the various beam figures are consistent in both Ta-10W and stainless steel
  - Very good surface quality welds correspond to consistent weld depth for each material
  - Directional figures deep and wider
  - High sulfur deeper than low sulfur due to Marangoni flow
  - Since there is spiking and only one cross section observed, depth measure is not accurate
- Figure Recommendation
  - For both Ta-10W and stainless steel, random figures at high frequency have very good surface quality and weld roots along with desirable weld depth